Thermal Generative Model for Energy Efficient Form Generation

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ABSTRACT: This paper develops a computer based Markov Chain model to generate prototype of architecture form with lowest heating primary heating energy demand with sufficient parameter input including surrounding environment data, urban configuration and architecture parameters.
This model also serves as a theoretical way to examine traditional energy efficient strategy in a multi-factor and evaluation based computer environment. In the latter part of the essay, several experiments are devised, executed and reported, arguing that the most energy efficient form varied in different climate environment, architecture configuration, material parameters, urban context and different energy criteria.

Keywords: Primary heating energy, Generative model, Energy efficient

1. INTRODUCTION

1.1 Strategic method

With decades of effort, energy efficient techniques have gained great development. Strategic method as one division of them focuses on a methodology to analyse and improve energy efficiency before architecture design. With analysis of climate data this division provides energy based advice for architect to determine the form of architecture at an early stage.

1.2 Generative model

Generative model is a computer based evolution model within which the configuration evolutes in a test-out method regarding to the evaluations of property in a Markov Chain.

Markov chain is a discrete-time stochastic process with the Markov property named after Andrey Markov. In such a process, the previous states are irrelevant for predicting the subsequent states, given the knowledge of the current state.[1]

A Markov chain describes at successive times the states of a system. At these times the system may have changed from the state it was in the moment before to another or stayed in the same state. The changes of state are called transitions. The Markov property means the system is memoryless, i.e. It does not "remember" the states it was in before, just "knows" its present state, and hence bases its "decision" to which future state it will transite, purely on the present, not considering the past.

In thermal generative model, the optimization is realized by several transitions, each transition is developed based on current state for the least primary heating energy demand in the next state.

2. METHODOLOGY

2.1 Standard Generation process

As a simplified description, thermal generative model took away each time one unit from the position with the best performance of the rest of the form and then relocated it into the position leading to the best performance of the new form.

The process comprises 3 transitions.

Transition1 Input initial environment parameters of N cubes representing the volume of character of the architecture and simulate the sunview in a predefined 3dmax maxscipt to calculate the projection areas. With image processing of Matlab and climate data from IWEC, the primary heating energy demand can be predicted by the balance of heat loss and solar gain.

Transition2 within N possibilities in the remove transition, take away each of the N cubes and evaluate the primary heating energy demand for the rest (N-1) cubes. The one with minimum primary heating energy demand for the (N-1) cubes is recorded to continue to transition 3.

Transition3 Relocate the taken away cube to the position indicated minimum primary heating energy demand. First, figure out all possible locations according to the site restriction and spatial connectivity. Then calculate the primary heating energy demand of each possible location. Once the best relocation position is the previous removing position in transition 2, then the process terminates. Otherwise, another circulation started from Transition1 for better energy performance.

In thermal generative model, numerous variables and calculations are involved to ensure a well-balanced model. The simplified process structure is illustrated in the figure 2.0.

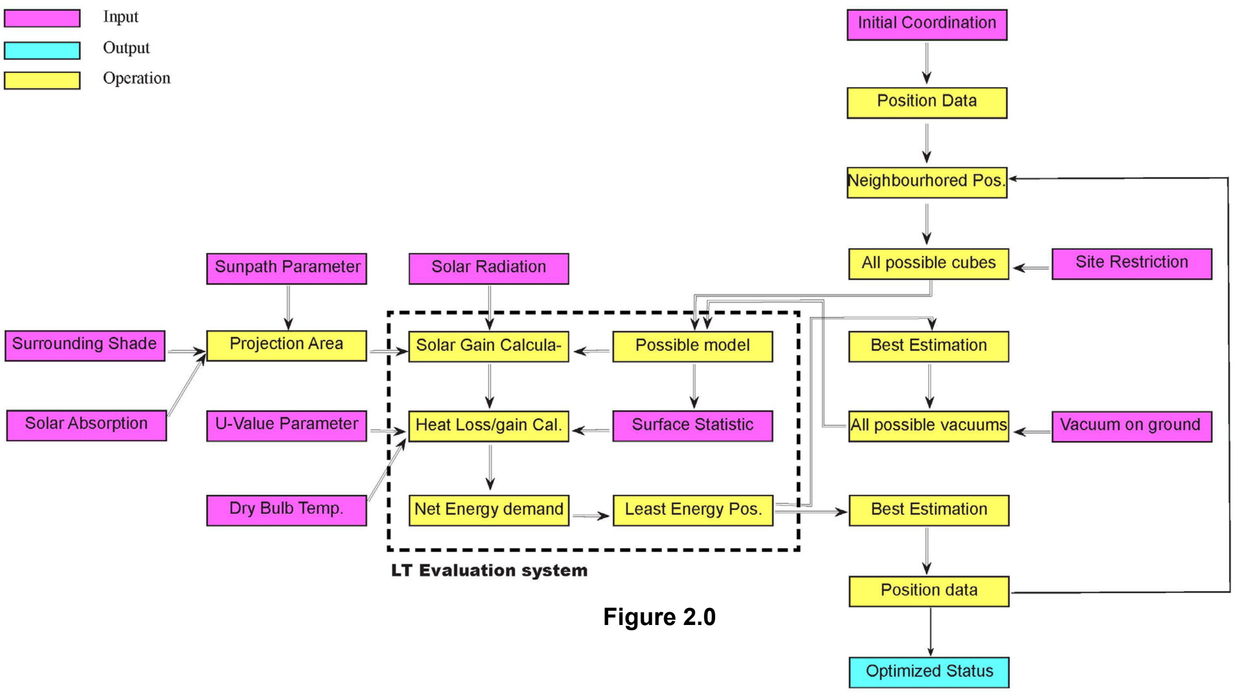


Figure 2.0

2.2 Primary heating energy Calculation

Thermal generative model is based on primary heating energy demand minimization. Primary heating energy demand is the sum of all the primary heating energy consumption before it is converted to deliver energy in the form of electricity and heat. Primary heating energy relates closely to CO_2 emission and other environment impacts assessment. Within this mechanism, thermal generative model contributes to environmental sustainability.

Primary heating energy demand is calculated in a single representative date. Net energy demand is calculated according to the sum of heating energy and cooling energy. Once the hourly or daily balance between solar gain and heat loss is minus, heating energy is demanded to warm up the underheated environment to ensure comfort. Otherwise the cooling energy is consumed to cool down the overheated environment to achieve comfort.

$$E_p=E_{hp}+E_{cp}$$

Due to the different mechanism of the heating and cooling appliance system, primary heating energy demand has different converting ratio in heating and cooling. Heating is achieved at a higher efficiency at while cooling can only be achieved by electrical air-conditioner with an efficiency as low[2] as 1/3.5.

$$E_{hp}= E_h *1.4$$

$$E_{cp}= E_c *3.5$$

Solar gain of this form is calculated by multiplying the projection area, radiation intensity and the heat gain coefficient (depending on different colour, glazing ratio and material heat absorption to describe the ratio of radiation).

$$E_{Solar\ Gain}= A_{Projection}*R_{Radiation}*k_{Heatgain}$$

Heat loss is calculated regarding parameters of U-value, surface area, ventilation rate, interior volume and temperature difference.

$$E_{heat\ Loss}= (1/3*N_{ventilation}*V+\sum U*A_{surface})*\ (T_{ext}-T_{int})$$

As the environment condition keeps changing from hour to hour, shift between heating and cooling causes the accumulation of energy consumption. Balance between the solar gain and heat gain/loss decides the heating and cooling demand hourly.

If $E_{Solar\ gain}+ E_{heat\ loss}>0$ then $E_{Solar\ gain}+ E_{heatloss}= E_{cp}$

If $E_{Solar\ gain}+ E_{heat\ loss}<0$ then $E_{Solar\ gain}+ E_{heatloss}= E_{hp}$

Considered architecture with or without thermal mass or with manual shading, all the heating and cooling are balanced hourly. The overall accumulation will be discussed in the chapter 2.5.

2.3 Description of complex architecture form

In the thermal generative model, architecture is simplified to be a number of cube units which is assumed to be 3m*3m*3m. Their locations are represented by matrix of 3d coordinations. Corresponding methods are developed to calculate the radiation area, surface area, material character and so on.

This syntax develops a logical and simplified description of complex form and relative energy performance. Also it provides a systematic framework to process the large amount of data at the same time guarantees the rational optimization with multiple parameters.

2.4 Climate Data Input

Three hourly based parameters are imported to thermal generative model: dry bulb temperature, normal solar radiation and sunpath angles. Dry bulb temperature is critical to calculate the heat loss. Direct normal solar radiation is used for solar gain calculation. Temperature and radiation intensity data referenced in this essay is referenced from IWEC data base3.

The sunpath parameters are simulated in 3dmax environment as a convenient way for projection area calculation.

2.5 Architecture Configuration Data Input

Three basic parameters describing architecture program and material are utilized: solar absorption coefficient, ventilation rate and U-value of the major components. Solar absorption coefficient is the average solar radiation absorption ratio for the facade related with glazing ratio, material colour and reflectancy. Facades with different orientation can be set with different configurations. Ventilation rate is the air exchange rate hourly regarding to service system. U-value of major components is the typical energy transfer parameter for the major architecture material. These three parameters can be decided by the architect and the engineer at the initial stage.

Three material thermal capacity parameters are considered in this model: high thermal mass, low thermal mass and manual shading. High thermal mass refers to an ideal configuration that the structure has a high heat capacity that can preserve the heat in its structure and energy demand is calculated on daily based:

$E_p = | \sum E_{heat\ loss} + \sum E_{Solar\ gain} |$

Low thermal mass refers to an ideal configuration where the structure has no heat capacity at all and energy demand is balanced hourly based:

$E_p = \sum(E_{heat\ loss} + E_{Solar\ gain})$

Manual Shading refers to a manual control of shading so that overheating can be avoided:

If $E_{Solar\ gain} > E_{heat\ loss}$ then $E_{cp} = 0$

If $E_{Solar\ gain} < E_{heat\ loss}$ then $E_{hp} = E_{Solar\ gain} + E_{heatloss}$

2.6 Urban Context Data Input

3 crucial urban context parameters are involved in this section: site boundary, urban geometry context and initial status. The site boundary is the limitation of the possible position, defined with the boundary of site and height restriction.

Urban shading context is described in the form of DEM (Digital Elevation Model) in 3dmax environment. Architectures and vegetation nearby serve as dynamic shading to the model in different time.

Initial status is the beginning state of all the units. Initial status will influent the result of optimization. This topic will be discussed in comparison of Experiment 8 and Experiment 2.

2.6 Primary heating energy Demand Data Output

As the evaluation criteria are the primary heating energy demand, the transfer rate of primary heating energy to heating effect and cooling effect is considered. All relative data is exported directly to an Excel file.

3. EXPERIMENTS AND RESULTS.

Basic Assumption

A villa of 243 square meters is located in a 21 meter by 21 meter site in a given city (Beijing or London). With different parameter, the most energy efficient architecture forms and corresponding strategies are tested.

The volume of this villa is assumed to be 729 cubic meter with an average floor height of 3 meters. The initial status is supposed to be an array of 27 cubes each 3 meter by 3 meter by 3 meter. The site limits permit the process operated in a 21*21*15m space for optimization.

3.1 Experiment 1 High thermal mass villa in winter Beijing

This experiment serves as a reference for the other experiments. The representative date is winter Beijing on Jan 15th.

With high thermal mass assumption, primary heating energy demand is the daily balance of total heat loss and solar gain with corresponding primary heating energy ratio.

As shown the initial status, total heat loss of the day is 333.1 Kwh and solar gain is 232.6 Kwh. The balance indicates in Jan 15th, 100.5 Kwh heating delivery energy demand is required from 140.7 Kwh primary heating energy.

In the first transition, one cube is taken away from the integration. As there are 27 cubes, the primary heating energy consumption of all 27 possibilities are calculated showing removing box located at (3,3,3) has a lowest primary heating energy performance at 137.76 Kwh. Then this cube is relocated to a possible location with the lowest primary heating energy demand. All 71 possibilities are tested and the location (2,5,3) has shown with a lowest Primary heating energy demand of 137.76 Kwh.

Shown in the series of illustrations of experiment 1 in figure 2.1, thermal generative model reaches a balance after 17 transitions. The primary heating energy consumption decreased from 140.7 Kwh to 3.2 Kwh. The efficiency of thermal generation in this experiment is 97.8%. The result reveals that energy demand can be obviously reduced in proper form with high thermal mass material.

3.2 Experiment 2 Low thermal mass villa in winter Beijing

With Low thermal mass predefinition, primary heating energy demand can be simplified to an hourly balance between heat loss and solar gain.

Between 8:00-9:00 of Jan 15th when exterior temperature is -4.1 Degree, the heat loss is 14.64Kwh and solar gain is 5.54 Kwh. The balance indicates between the 8:00-9:00 in Jan 15th, 9.1Kwh heating delivery energy demand is gained from 12.74Kwh primary heating energy consumption. Primary heating energy demand for the whole day is 845Kwh.

In the first transition, one cube is taken away from the integration with the lowest Primary heating energy demand of 815 Kwh at location (3,5,3). Then this cube is relocated to the location (4,2,2) with a lowest primary heating energy demand of 816 Kwh.

According to the process of experiment 2 in figure 2.2, the thermal generative model reaches a balance after 12 transformations. The primary heating energy consumption decreased from 845.3 Kwh to 655.3Kwh. The efficiency of thermal generation in this experiment is 22.5%.

The final result of Experiment 2 indicates a form for minimization of solar gain. There are two reasons for this result:

1. The solar radiation (refer to the climate data from IWEC) in winter Beijing is even stronger than summer Beijing and this experiment is assumed to be an ideal environment with no thermal mass at all. Thus no heat from solar radiation can be store for night heating. Hourly based calculation indicates a huge cooling demand in the daytime.

Figure 2.1 Experiment 1
HWB:
FullThermomass
Winter-Beijing
140.7 to 3.1Kwh/Day
Efficiency 97.8%

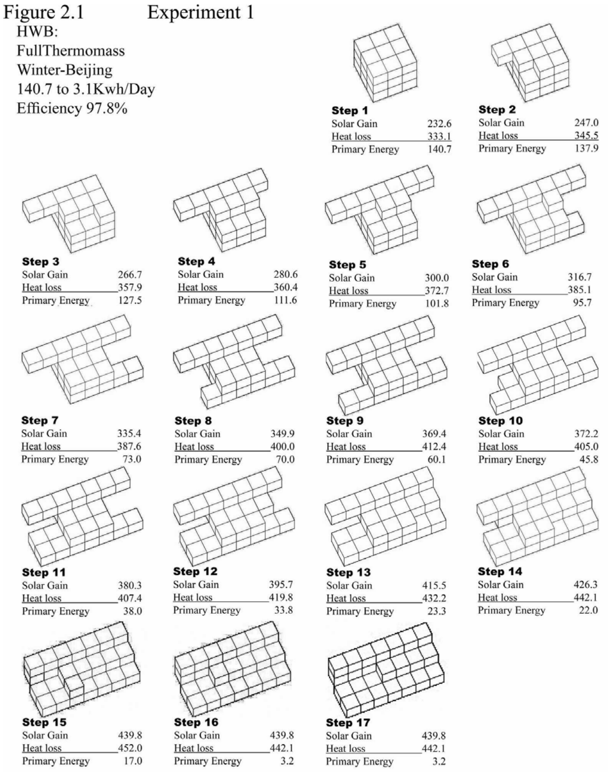


Figure 2.2 Experiment 2
LWB:
NonThermomass
Winter-Beijing
845.3 to 655.3Kwh/Day
Efficiency 22.5%

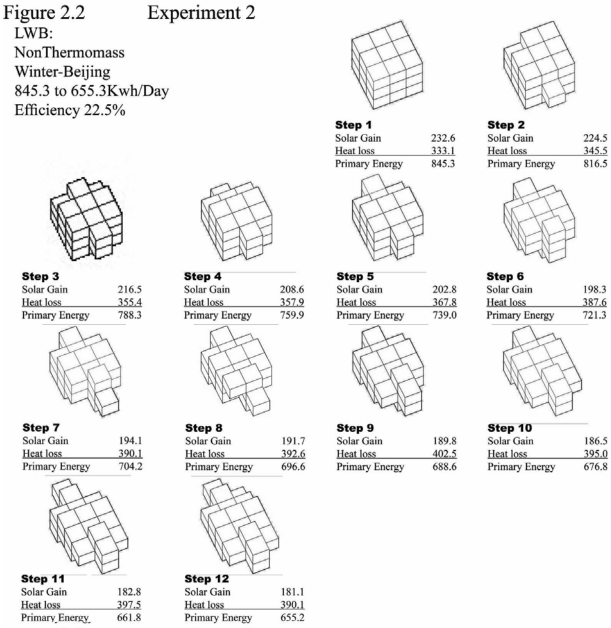


Figure 2.3 Experiment 3
MWB:
Manual shading control
Winter-Beijing
334.1 to 334.1Kwh/Day
Efficiency 0%

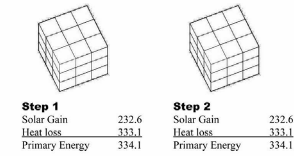
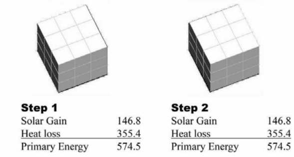


Figure 2.4 Experiment 4
SWB:
Fix Shaded Facade
Winter-Beijing
574.5 to 574.5Kwh/Day
Efficiency 0%



Generative model is based on primary heating energy demand where electrical cooling is two times more expensive than hot water heating. So the generative model will prefer the heating to cooling.

3.3 Experiment 3 Manual shading villa in winter Beijing

This experiment simulates a house with manual shading control for example blinds and curtains on the facade to prevent solar gain from overheating period.

Referring from experiment 1, no thermal mass is considered and all energy exchange is calculated in an hourly balance. The mechanism of manual shading control model assumes if any overheating is detected, shading is assumed to be activated so that excessive heating is prevented outside the building.

Illustrated in the figure 2.3, the experiment result indicates that primary heating energy demand can not be reduced in Generative model. Also, energy demand is already much less than building without manual shading system illustrated in the experiment 2.

3.4 Experiment 4 different property of facade in winter Beijing

This experiment simulates different radiation absorption ratio on facade in different orientation to explore the influence of comfort performance and corresponding building blind strategies. Traditionally, east and west facades are thought to suffer more from overheating. The method is to assign different materials in boxes' six facades in 3dmax environment so that darker facade indicates less radiation absorbed in Matlab environment. In this experiment, the west facade solar projection ratio is assigned 20% and east facade solar projection ratio is 40% while south facade solar projection ratio is 60%

The same as in experiment 2 and 3, no thermal mass is considered in this experiment. Illustrated in the figure 2.4, the fixed shading is less flexible than the manual shading in experiment. Primary heating energy demand is 50% higher of the manual shading model.

However, this experiment can not be optimized for less energy performance with thermal generative model.

3.5 Experiment 5 Initially flat Low thermal mass villa in Winter Beijing

This experiment explores the influence of initial status of thermal generative model. Thermal generative model is a Markov chain which relies on evolution in current state. Thus it is necessary to test in what way and to what extent the initial status influences generative performance.

This experiment has the same configuration with the experiment 2 except for a flat initial status. This constitutes a sample of thermal generative method. The result in figure 2.8 illustrated that flat initial state will lead to a slightly inefficient final performance. Flat initial status in winter is inefficient in energy term because of its large heat loss area. Its primary heating energy demand as high as 1049 Kwh is 150% to the cube initial experiment. However, after 19

Figure 2.5 Experiment 5

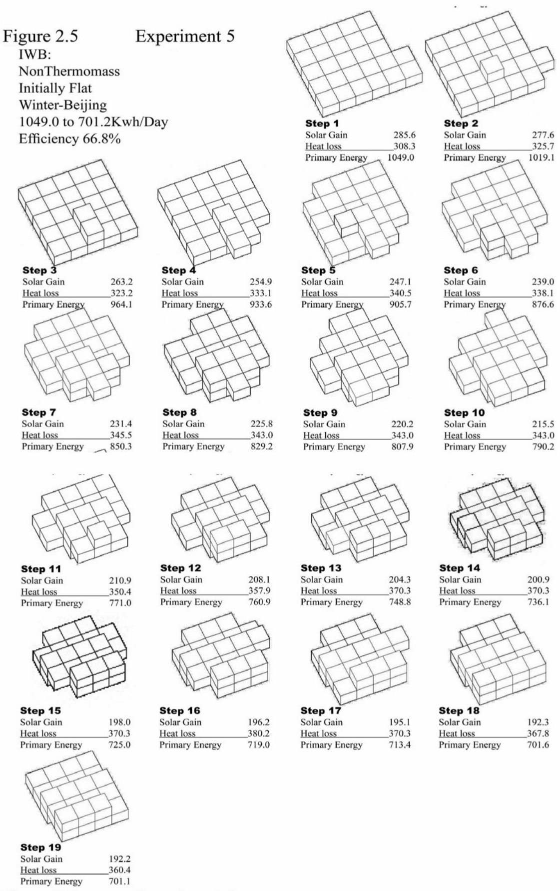


Figure 2.6 Experiment 6

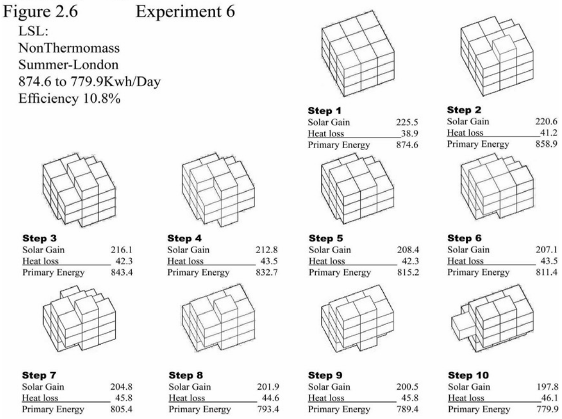
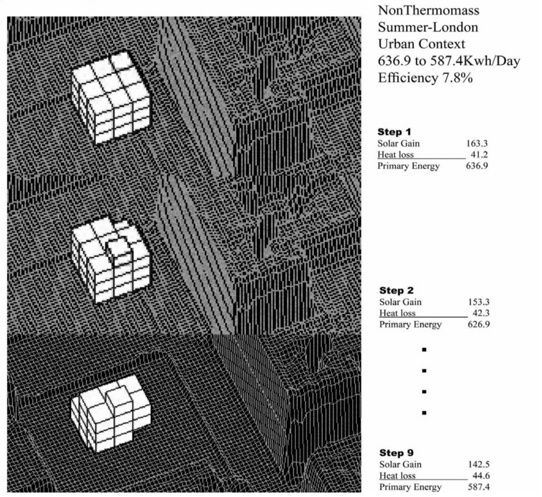


Figure 2. 7 Experiment 7



transitions of optimization, its primary heating energy demand, 701Kwh, is similar to the cube experiment 655Kwh. However, their ultimate form is different

Examination of the initial status is critical for thermal generative model. Not all the initial forms can be optimized to the 'most energy efficient form'.

3.6 Experiment 6 Low thermal mass Villa in Summer London

This experiment has two purposes: to test the thermal generative model in a different climate and serve as a reference for experiment 10 to discuss the influence of urban context.

This experiment has the same configuration as the experiment 6 besides the location of climate zone. The main differences lie in the climate data and the solar angles.

The result for summer Beijing is a cube. However, according to the result illustrated in figure 2.9, the result for London is rather a radiation minimized one. The try bulb temperature in summer London is lower than the predefined comfort temperature which means all-day heat loss. Thus the climate pattern is rather similar to the experiment 7 in the spring Beijing. However energy consumption is much less than the Beijing spring situation because of the less severe change is temperature. After 10 transformations the primary heating energy demand is lowered down from 874.6 Kwh to 774.9 Kwh with an efficiency of 10.8%.

3.7 Experiment 7 Low thermal mass villa in Summer London with Urban context

This experiment examines the influence of shading of urban context. All configuration of experiment 10 is the same as experiment 9 except the introduction of an urban context of London Tottenham Court Road in the format of DEM.

This experiment is the application of generative model in urban context. The simulation in 3dmax environment indicates reduced solar radiation blocked by urban context. Total solar gain in the initial status is 163.3Kwh which is significantly less than 225.5Kwh in the previous experiment. The result illustrated in the figure 2.10 shows that the strategy to minimize the solar gain within urban context is similar to the experiment 9.

Another reason for this ultimate form is the incapacity of initial location to reach the shadow of the nearby building. The application of thermal generative model in urban context influences the primary heating energy by reducing cooling demand. Given in a more extreme climate and compact context the shape transformation can be more obvious. After 9 transitions of transformation the primary heating energy is reduced from 636.9Kwh to 587.4Kwh with an efficiency of 7.8%.

4. FUTURE DEVELOPMENT

4.1 Integrated optimised form

In this version, the thermal generative model is based on primary heating energy demand in the climate data of a single day which is representative of a season. It would be necessary to integrate an optimised form for the whole year round.

4.3 Optimized Markov Chain

Evolution in the Markov Chain is developed with only the optimization on the current one transition. However, the transition by transition optimization may not finally lead to a minimum form because of its myopia. Thus a strategic Markov Chain or Generative method may help to optimize the shape to the extreme. Another problem is the equal value determination, in some occasions the primary heating energy demand came across the same in different possibilities. A strategic method to select one from them is crucial in Markov Chain.

4.4 Open Evaluation Structure

This model is drived by simplified heat primary energy in Markov Chain. Similar evaluation can also be considered in this structure such as lighting, ventilation. With further development and evaluation of wind flow and lighting energy, this model is possible to be developed for real world simulation environment which is similar to architect theoretical thinking. Mixed parameter will integrate consideration other than energy consumption.

4.5 Self Subdivision

Sub-divide process is a strategy to simplify the computational expensive linear calculation especially in large scale. If LTG model uses same methods to deal with architecture in different scales at the same time, the model would be extraordinarily inefficient.

A proper solution to this is to establish a hierarchical system of sub-division. Take a 1000000-cubic-meter architecture for example. In the highest hierarchy, a system made up of 64 25*25*25 meter cubes. After the generative model in highest hierarchy, an energy efficient framework of lower hierarchy is established. Then the system is sub-divided into 125000 5*5*5 meter lower hierarchy. As the higher framework is well established, the computation would be much efficient than linear calculation.

5. CONCLUSION

As an optimization tool and design assistant, thermal generative model assists early stage design to minimize energy demand.

The limit of this model is the oversimplified Markov Chain Method and heating energy consumption calculation. With further development, thermal generative model can be quicker and more accurate.

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REFERENCES

[1] Wikipedia.org. 1.2006

[2] Nick Baker & Koen Steemers, ‘Energy and Environment in Architecture’, 2000

[3] Chen Shuo, ‘Enquiry the energy efficient form with THERMAL Generative model’, Appendix 1, 2005